Original Article

C-arm Cone Beam Computed Tomography: A New Tool in the Interventional Suite

Santhosh Raj,[1] *MBBS, FRCR*, Farah Gillan Irani, [1] *MBBS, FRCR, FAMS*, Kiang Hiong Tay, [1] *MBBS, FRCR, FAMS*, Bien Soo Tan, [1] *MBBS, FRCR, FAMS*

Abstract

Introduction: C-arm Cone Beam CT (CBCT) is a technology that is being integrated into many of the newer angiography systems in the interventional suite. Due to its ability to provide cross sectional imaging, it has opened a myriad of opportunities for creating new clinical applications. We review the technical aspects, current reported clinical applications and potential benefits of this technology. Materials and Methods: Searches were made via PubMed using the string "CBCT", "Cone Beam CT", "Cone Beam Computed Tomography" and "C-arm Cone Beam Computed Tomography". All relevant articles in the results were reviewed. Results: CBCT clinical applications have been reported in both vascular and non-vascular interventions. They encompass many aspects of a procedure including preprocedural planning, intraprocedural guidance and postprocedural assessment. As a result, they have allowed the interventionalist to be safer and more accurate in performing image guided procedures. There are however several technical limitations. The quality of images produced is not comparable to conventional computed tomography (CT). Radiation doses are also difficult to quantify when compared to CT and fluoroscopy. Conclusion: CBCT technology in the interventional suite has contributed significant benefits to the patient despite its current limitations. It is a tool that will evolve and potentially become an integral part of imaging guidance for intervention.

Ann Acad Med Singapore 2013;42:585-92

Key words: Angiogram, Biopsy, Embolisation, Intervention, Stenting, Vascular

Introduction

C-arm Cone Beam CT (CBCT) is a relatively new technological advancement in the interventional suite which employs a flat panel angiographic system to produce computed tomography (CT) like cross sectional multiplanar and three-dimensional (3D) images. It brings a higher level of confidence and accuracy to the interventionalist by allowing the manipulation of imaging data in new ways.[1, 2]

The first adaptation of CBCT into potential clinical use began at the Mayo Clinic Biodynamics Research Laboratory in 1982.[3] At that time, its development focused mainly on the visualisation of high contrast structures such as bone and contrast in vessels. In 1999, the first linear accelerator with an integrated CBCT system was developed to guide radiation therapy.[4] In 2001, the first commercially available CBCT system (NewTom QR DVT 9000; Quantitative Radiology, Verona, Italy) showed its potential in dentomaxillofacial imaging.[5] The detailed cross sectional images were useful in solving complex diagnostic and treatment planning problems such as in dental implants, orthodontics and complex craniofacial fractures.[6-10] All this was performed in the dental office without having to scan the patient separately in a conventional CT scanner.

The initial adaptation of CBCT in the interventional suite was better known as '3D angiography'. This implementation enabled only visualisation of bone and vessels with contrast. Although this was a significant step in angiographic imaging, improved computational algorithms and computer processing power soon enabled the visualisation of even low contrast soft tissue structures. This resulted in CBCT as we know it today.

In this paper, we review the technical aspects and the current clinical applications of CBCT in interventional radiology and discuss the potential benefits of this new technology.

[1]Interventional Radiology Centre, Department of Diagnostic Radiology, Singapore General Hospital, Singapore
Address for Correspondence: A/Prof Tan Bien Soo, Interventional Radiology Centre, Department of Diagnostic Radiology, Singapore General Hospital, Outram Road, Singapore 169608.
Email: tan.bien.soo@sgh.com.sg

Technical Aspects

Technical Construct

CBCT has become available in the interventional suite as older angiography machines with image intensifiers have been replaced by new angiographic units using flat panel detectors made from cesium iodide (CsI) scintillators. As shown in Figure 1A, aside from the detector, the construct of the angiographic machine consists of a C-arm, an X-ray source and the patient table. Image processing is performed by backend computer systems that receive data directly from the angiography machine. Image viewing and manipulation is then performed by frontend computer systems that receive the processed data from the backend systems.

Another commercially available system which also performs cross sectional imaging in the interventional suite is the hybrid CT angiography system. It however differs from a CBCT system in that it has an additional conventional CT machine which when placed in the interventional suite would take up additional space.

Imaging

Imaging with CBCT involves 2 phases, namely image acquisition and image reconstruction.

Image acquisition involves the projection of a cone shaped (wide collimation) X-ray beam from the X-ray source onto the flat panel X-ray detector (Fig. 1B). At the same time, the X-ray detector and X-ray source rotate around the patient taking multiple images which are sent to the backend computer systems for processing. With CBCT, a complete data volume set is acquired in one single rotation.

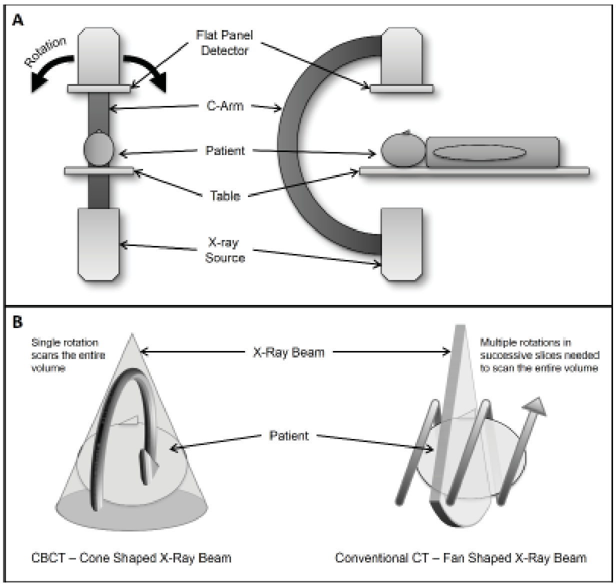

Fig. 1. (A) is a diagrammatic representation of a typical construct in a CBCT system. (B) is a diagram showing the difference in X-ray geometry of CBCT and conventional CT.

In contrast, a conventional CT machine emits a fan-shaped X-ray beam of narrow collimation which requires multiple rotations around the patient in successive slices to acquire the same data volume set.

Image reconstruction involves conversion of received data by backend computer systems into 3D images via a backprojection algorithm modified from the initial work described by Feldkamp.[11] This is a more complex and time consuming process as the data sets are acquired through a cone beam projection in contrast to a fan beam used in conventional CT. Thus, a CBCT system requires about 1 minute for image reconstruction in contrast to conventional CT which processes the data in almost real-time.

The converted 3D image data is then sent to frontend systems that consist of computer workstations that can be manipulated by the radiographer or interventionalist. On the workstation, the images can be visualised in multiplanar reconstruction formats similar to conventional CT images. The images can also be volume rendered in 3D (volume rendering technique (VRT)) to give the interventionalist a better spatial sense of the targeted lesion. Further advancements in software and hardware technology have also made it possible to mark the targeted lesion and plan a trajectory on the workstation. The information can then be superimposed on the fluoroscopic image in the interventional suite to guide the approach to the lesion.

Limitations

A significant difference between a CBCT system and a conventional CT is the increased scatter generated in the former due to the wider collimation of a cone beam.[12] The resultant degradation of image quality is due to loss of signal to noise ratio, increased artifacts and inaccuracies in CT number calculations (Hounsfield units). There are potential solutions to reduce the amount of scatter, but none of them are comprehensive at present. An example of an existing method to reduce scatter is the employment of anti-scatter grids and air gaps which are used in fluoroscopy and general radiography. In a CBCT system, this method has shown to significantly reduce X-ray scatter, thus improving the accuracy of CT numbers, reducing streak artifacts and increasing the signal to noise ratio. However, the resultant increase in radiation dose to the patient indicates that there is still much room for improvement.[2]

In addition, CsI scintillators used in the X-ray detectors of a CBCT system also have a longer lag (afterglow) when compared to the ceramic detectors used in conventional CT. This results in reduced number of images taken per image acquisition, which further contributes to streak artifacts. Motion artifacts are also more prominent due to increased acquisition time.

Radiation Dose

The topic of radiation dose in CBCT is a complex one. There is no standardised way to compare doses between a CBCT system and conventional CT. The dose length product (DLP) used in a CBCT system does not correlate with CT dose index (CTDI) used in conventional CT due to differences in the X-ray beam geometry. Theoretically, as the collimation in CBCT is wider than in conventional CT, the radiation doses are potentially higher. Several studies have attempted to compare patient doses using phantoms and their results have been variable. Hirota et al showed that when compared to a single slice CT, radiation doses in CBCT were lower.[13] Koyama et al however showed that radiation doses were similar between multi slice CT and CBCT.[14] More recently, Suzuki et al showed that radiation doses were also variable between systems by different vendors and also between different sized phantoms.[15]

Since the purpose for the use of CBCT is to reduce procedural time by making available cross sectional imaging for interventional guidance, the overall radiation dose could potentially be lower. However, if used injudiciously, it could still result in overall higher radiation doses. Thus its use and impact in clinical practice should be investigated further.

Clinical Applications

Interventional procedures can broadly be divided into vascular and non-vascular interventions. Vascular intervention involves procedures performed via the arteries and veins such as embolisation, angioplasty and stenting. Non-vascular intervention encompasses procedures that are performed percutaneously or endoluminally in organ systems beyond the vascular system such as biopsies, drainages and nephrostomies. In both types of intervention, CBCT enhances the accuracy and safety, and potentially reduces procedural time. This is further aided by software and hardware which dynamically guide needle or catheter positioning.

CBCT also allows immediate post-treatment assessment and detection of procedure related complications without having to move the patient to a conventional CT machine. This saves time and potentially enables faster initiation of treatment modifications and management of complications.

Another indirect benefit of CBCT is the potential for lower contrast use. This is primarily due to reduced catheter manipulation time compared to using standard 2-dimensional angiographic images alone to plan and guide treatment.

Non-vascular Intervention

Accurate percutaneous targeting of a lesion by image guidance is an important aspect of non-vascular intervention.

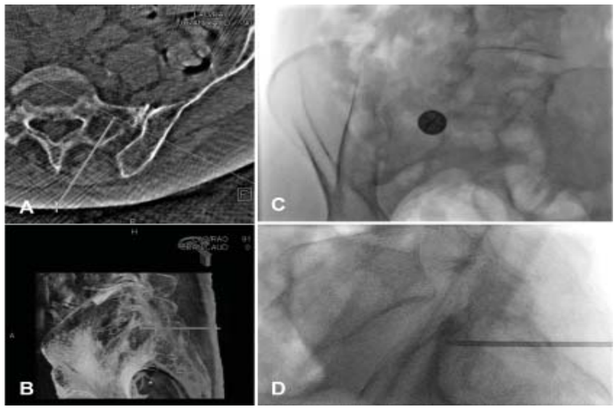

Fig. 2. Sacral biopsy. (A) CBCT cross sectional images together with software guided needle positioning were used to plan the target in the left sacral ala for biopsy. (B) Three-dimensional MIP sagittal view shows the needle position in a view similar to what is expected on fluoroscopy. (C) During needle positioning, the C-arm is moved to the bull's eye view for needle placement. (D) Once the needle is placed halfway through the skin, the C-arm is then moved to the needle progression view to assess the needle depth.

Additional information in the form of cross sectional imaging allows the interventionalist a higher level of confidence and accuracy in planning the needle trajectory. To illustrate, CT guided transthoracic lung biopsy is a common procedure performed by the interventionalist on a conventional CT machine. Recent publications on CBCT guided lung biopsies have shown comparable results to CT, with sensitivity, specificity and diagnostic accuracies of 90%, 100% and 91.7%, respectively.[16] Percutaneous spinal interventions have also benefited from CBCT's enhanced accuracy. Technical success rates of 75% to 100% have been reported for vertebroplasties using needle guidance software.[17] Various other spine and pelvic procedures have benefitted from CBCT as well, including biopsies (Fig. 2) and abscess drainages.[18,19] CBCT has also been used to guide therapy for spinal osteoid osteomas both for placement of paraspinal fiducial markers and for radiofrequency ablation.[19,20]

The use of CBCT has extended to other areas of the body as well. In cases where a lesion is not well demonstrated on ultrasound (US), CBCT offers an additional option to conventional CT. For hepatic tumours that are too deep for optimal US visualisation, CBCT can be helpful in targeting these lesions for radiofrequency ablation.[21] For renal biopsies, CBCT helps the visualisation of lesions and allows the procedure to be performed with needle guidance software.[22]

New ways to guide procedures such as percutaneous gastrostomy catheter insertion have also been made possible. Conventionally, it is performed under fluoroscopic and ultrasound guidance only. However, with multiplanar cross sectional images available with CBCT, the exact location

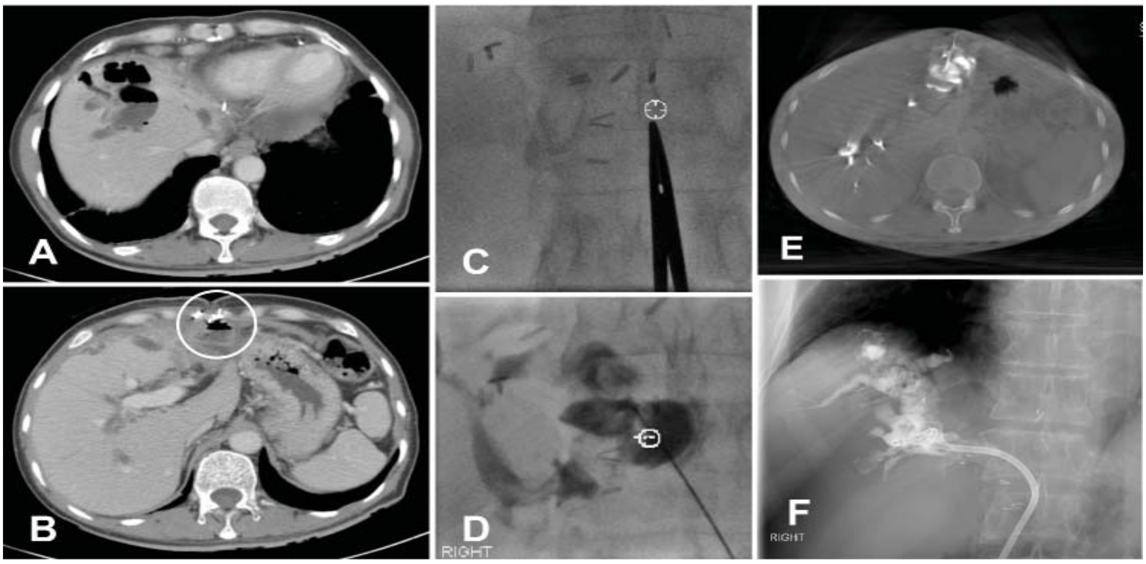

Fig. 3. A 62-year-old male, post hepaticojejunostomy with recurrent cholangitis. (A, B) Conventional CT images showing dilated bile ducts with an air fluid level compatible with obstruction and cholangitis. Afferent limb of the Roux-limb (circle) is fixed to the anterior abdominal wall. (C) With CBCT and software guided needle positioning, the exact location of the Roux-limb was determined and punctured. This was then confirmed with contrast injection (D) and CBCT (E). (F) Final cholangiogram shows the biliary drain catheter to be satisfactorily positioned.

of the stomach can be determined and percutaneously punctured using needle guidance that is projected on live fluoroscopy.[23] Another similar application involves percutaneous access of an obstructed biliary system for drainage after a surgical hepaticojejunostomy. Using CBCT, the roux-limb that has been fixated to the anterior abdominal wall can be localised and punctured for subsequent retrograde placement of a biliary drainage catheter across the strictured hepaticojejunostomy (Fig. 3).

CBCT is also able to provide an immediate assessment of the completeness of interventional treatment that is more accurate than 2-dimensional fluoroscopic images alone. For example, in vertebroplasty, the distribution of cement within the treated vertebra can be assessed in the interventional suite.[24]

Early assessment of procedural complications is another important advantage of CBCT. For vertebroplasty, CBCT showed a 91% detection rate of cement leak when compared to conventional CT.[24] For lung biopsies, pneumothoraces could also be detected even when they were too small to be seen on fluoroscopy alone.[25]

Vascular Intervention

In vascular intervention, the first application of CBCT was described in neurointervention, with the report of the use of CBCT to assess for suspected intracranial hemorrhage in 3 cases intraprocedurally.[26] In 2 of the cases where intracranial haemorrhage was detected, earlier diagnosis and management was possible without moving the patient to a conventional CT machine. Diagnostic angiography for neurointerventional treatment planning also benefitted from CBCT's ability to characterise lesions better. For example, better assessment of carotid cavernous fistulas (CCF) and spinal dural arteriovenous fistulas (SDAVF) enabled the treatment choice between endovascular or surgical techniques to be made.[27,28] Recently, CBCT has been shown to provide better assessment of stent deployment in intracranial stenting.[29] Immediate post-stenting problems such as mal-apposition, calcification along the stented segment and filling defects within the stent could be detected and treated accordingly.

The use of CBCT in vascular intervention has expanded to other areas of the body. One of the main advantages of CBCT is that it is able to identify a target lesion accurately. Two fairly common procedures performed in the interventional suite today for the treatment of hepatic tumours are transarterial chemoembolisation (TACE) and hepatic Yttrium-90 (Y90) infusion,[30,31] both of which involve the arterial infusion of a target lesion within the liver using various agents. Certain lesions that are not well demonstrated on digital subtraction angiography (DSA) are better appreciated on CBCT (Fig. 4). Accurate catheterisation of the tumour feeding artery is also enhanced by 3D vascular mapping available through CBCT. This avoids multiple DSA runs in various projections and helps reduce procedural time, contrast load and radiation exposure. Non-hepatic tumour embolisation procedures such as for pancreatic head tumours and renal metastases, have also benefited in the same way.[32]

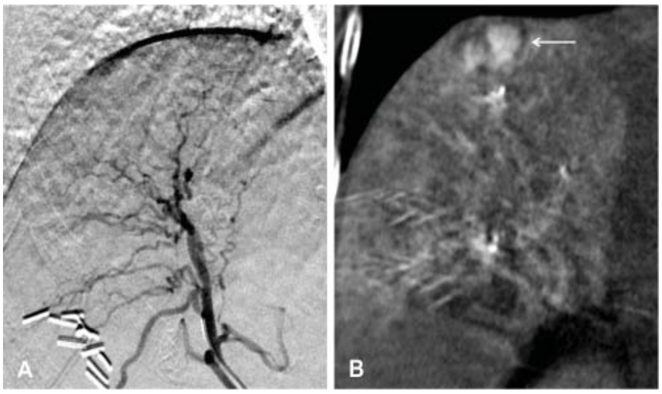

Fig. 4. Patient with history of hepatocellular carcinoma with a new hypervascular nodule at the dome in segment 7 detected on diagnostic 3 phase CT of the liver. (A) DSA of the right hepatic artery during TACE could not demonstrate the nodule. (B) CBCT with intra-arterial contrast injection through the catheter demonstrated the nodule (arrow) clearly and embolisation was subsequently performed.

Fig. 5. A 59-year-old man with hepatocellular carcinoma (HCC) referred for Y-90 radio-embolisation. (A) Diagnostic CT showed the HCC to be in segment 2/3 (white arrowhead) of the liver. (B, C) DSA images showed the left hepatic artery (black arrowhead) arising from the common hepatic artery. Two areas of contrast blush were noted on DSA (white arrows) and it was uncertain whether both represented tumour or not. (D, E) CBCT showed that the upper contrast blush was enhancement of the gastric mucosa from an accessory left gastric artery arising from the left hepatic artery. (F) The accessory gastric artery was subsequently embolised in view of treatment with Y-90.

Avoiding the delivery of drugs and embolic material into non-target organs in vascular intervention is of paramount importance. In TACE and Y90 infusion therapy, non-target vessels such as the gastroduodenal artery (duodenum), right gastric artery (stomach) and the accessory left gastric artery (stomach) (Fig. 5) can be confidently demonstrated by CBCT and safely avoided or embolised prior to delivery of the drug or infusion.[33] Similarly in bronchial artery embolisation, identification of spinal artery supply is important to avoid the complication of spinal cord infarction. When spinal artery supply is suspected, CBCT is able to assess this further by providing a more detailed 3D vascular map (Fig. 6).

A significant portion of time taken during an interventional procedure involves intraprocedural treatment planning. CBCT has been especially helpful in TACE for hepatic tumours that have multiple arterial supply. It can show a distribution map of each arterial supply to the tumour so that the appropriate chemoembolic dose can be titrated for each artery.[34] Partial splenic embolisation for the treatment of hypersplenism has also benefitted from CBCT where good outcomes were shown when 60% to 70% of the spleen was intentionally infarcted.[35]

CBCT similarly is able to assess the completeness of treatment while the patient is still in the interventional suite. In TACE, treatment coverage can be assessed by imaging the distribution of lipiodol uptake within the tumour.[33,36] For endovascular aortic repair (EVAR), stent apposition to the aortic wall and the detection of endoleaks can be imaged as well.[37] Following deployment of an inferior vena cava (IVC) filter, DSA alone may not be adequate in assessing

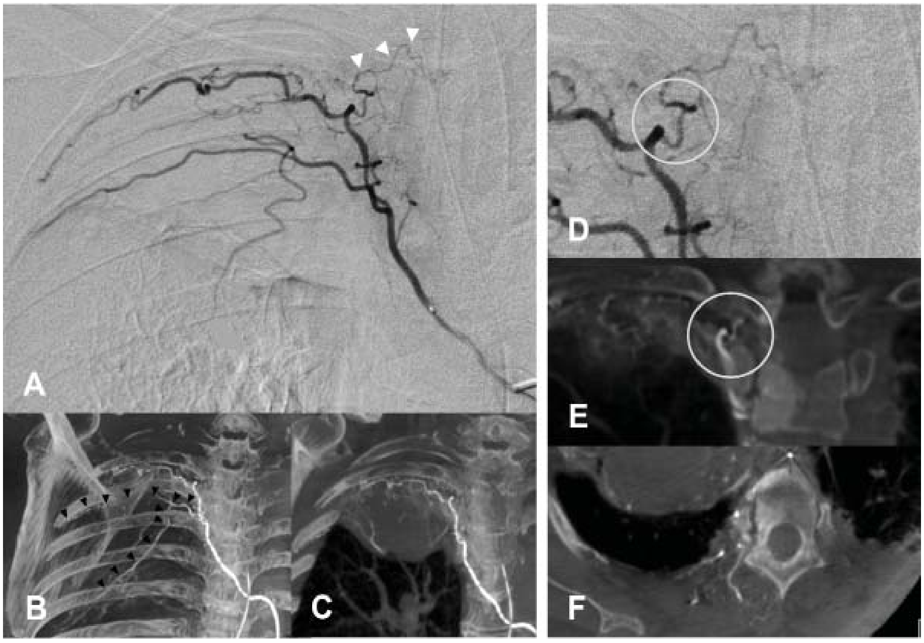

Fig. 6. A patient with haemoptysis was referred for bronchial artery embolisation (BAE). (A) On DSA, there are 2 right intercostal arteries arising from a common origin. With DSA alone, it was difficult to determine if any of these vessels were supplying the right apical lung. Of note (white arrowheads), were tiny suspicious vessels that were coursing towards the midline. These were indeterminate for supply to the spinal cord. On CBCT, both intercostal arteries were demonstrated exquisitely. The lower one (B) did not show any supply to the lung (black arrowheads), however the upper branch (C) was supplying the right lung apex. (D) Zoomed up view of (A) shows the suspicious vessels coursing towards the midline (circle). On CBCT (E, F) it was shown to be arising from the superior intercostal branch (circle) but did not supply the spinal cord. Patient was subsequently treated with selective embolisation of the branch that was supplying the lung.

final filter position. With CBCT, this assessment is clearer and helps decide if there is need for repositioning (Fig. 7).

CBCT has a myriad of other potential clinical applications in the vascular arena. Its use has been reported in procedures such as portal vein embolisation, insertion of translumbar IVC central venous catheters,[38] and injection sclerotherapy for slow flow vascular malformations.[39]

Future Direction and Challenges

Many vendors are incorporating CBCT into their angiographic systems with various trade names. One of the strongest benefits in terms of equipment procurement is that CBCT only involves 1 machine being in the interventional suite as compared to 2 in a hybrid CT angiography system. Besides needing a smaller room than a hybrid system, a CBCT system should cost less to run and maintain in the long term. Improved logistics is also expected as CT guided procedures can be performed in the interventional suite, freeing the conventional CT equipment for diagnostic work.

There are still challenges that CBCT faces prior to wider acceptance in interventional radiology practice. Some of the limitations however, such as inaccuracies in CT number and image artifacts do not significantly affect the performance of an interventional procedure. Imaging capabilities of current commercially available systems are more than adequate to guide procedures, and provide on table pre- and post-procedural assessment. However, further improvement in imaging capabilities is expected as software and hardware technology continue to advance.

CBCT imaging times can also be further improved. Although patient need not be moved to a conventional CT machine, the overall time taken to acquire and reconstruct images is still longer than that taken by conventional CT. Nevertheless, with increased familiarity and continued improvement in workflow, CBCT imaging should become more efficient.

Another challenge that concerns CBCT is radiation dose, which has been discussed earlier in this article. The overall impact of the use of CBCT in clinical practice on radiation dose to the patient is still unclear, and more work is needed to further assess this.

Conclusion

CBCT has brought a new dimension of visualisation into the interventional suite. Although there are still challenges, current systems provide the interventionalist with images not obtainable with fluoroscopy, DSA or US. These images have allowed the interventionalist to be safer and more

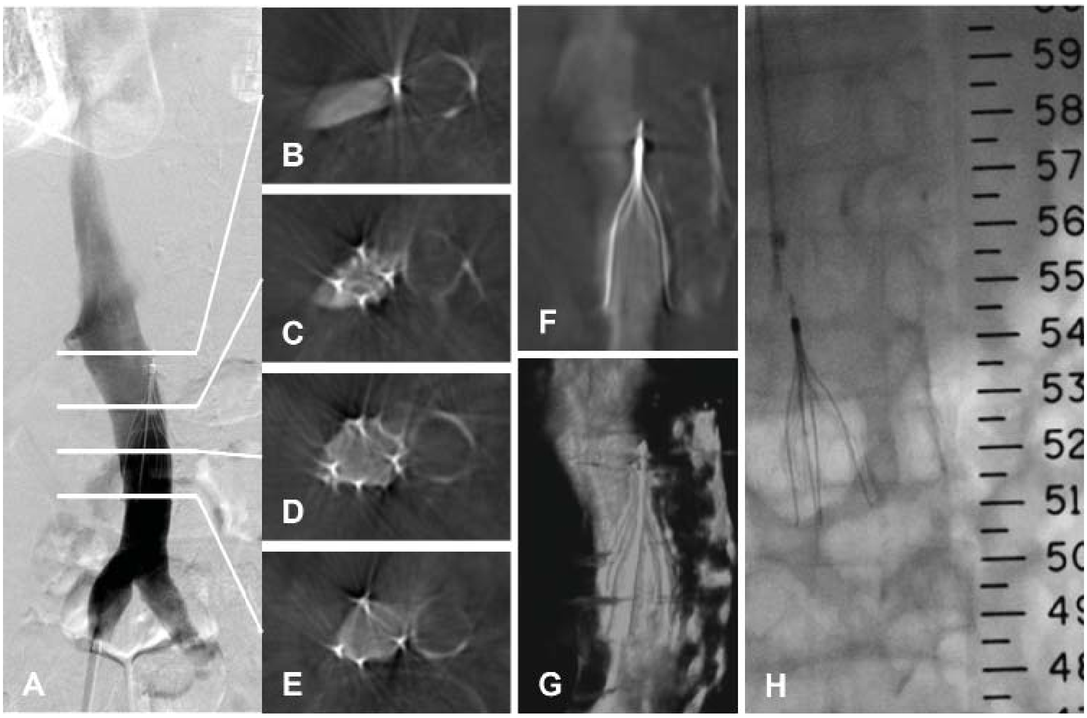

Fig. 7. Insertion of an IVC filter. (A) Initial insertion from a right common femoral vein approach resulted in very oblique deployment of the filter in the IVC. This was better demonstrated on CBCT multiplanar and 3D reconstructions (B-G). It showed that the hook at the apex of the filter was indenting the caval wall significantly. Decision was thus made to retrieve the filter and redeploy it from a transjugular approach with a more central final position (H).

accurate. CBCT has also increased the flexibility of the interventional suite by enabling CT guided procedures to be performed. It however will not replace conventional CT machines for diagnostic imaging.

CBCT technology will continue to evolve and improve. It is a new tool that will potentially become an integral component of the imaging equipment in the interventional suite.

REFERENCES

1. Wallace MJ, Kuo MD, Glaiberman C, Binkert CA, Orth RC, Soulez G. Three-dimensional C-arm cone-beam CT: applications in the interventional suite. J Vasc Interv Radiol 2008;19:799-813.
2. Orth RC, Wallace MJ, Kuo MD. C-arm cone-beam CT: general principles and technical considerations for use in interventional radiology. J Vasc Interv Radiol 2008;19:814-21.
3. Robb RA. The dynamic spatial reconstructor: an x-ray video-fluoroscopic CT scanner for dynamic volume imaging of moving organs. IEEE Trans Med Imaging 1982;1:22-33.
4. Jaffray DA, Drake DG, Moreau M, Martinez AA, Wong JW. A radiographic and tomographic imaging system integrated into a medical linear accelerator for localization of bone and soft-tissue targets. Int J Radiat Oncol Biol Phys 1999;45:773-89.
5. Miracle AC, Mukherji SK. Conebeam CT of the head and neck, part 2: clinical applications. AJNR Am J Neuroradiol 2009;30:1285-92.
6. Guerrero ME, Jacobs R, Loubele M, Schutyser F, Suetens P, van Steenberghe D. State-of-the-art on cone beam CT imaging for preoperative planning of implant placement. Clinical Oral Investig 2006;10:1-7.
7. Nakajima A, Sameshima GT, Arai Y, Homme Y, Shimizu N, Dougherty H Sr. Two- and three-dimensional orthodontic imaging using limited cone beam-computed tomography. Angle Orthod 2005;75:895-903.
8. Terakado M, Hashimoto K, Arai Y, Honda M, Sekiwa T, Sato H. Diagnostic imaging with newly developed ortho cubic super-high resolution computed tomography (Ortho-CT). Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2000;89:509-18.
9. Ziegler CM, Woertche R, Brief J, Hassfeld S. Clinical indications for digital volume tomography in oral and maxillofacial surgery. Dentomaxillofac Radiol 2002;31:126-30.
10. Drage NA, Sivarajasingam V. The use of cone beam computed tomography in the management of isolated orbital floor fractures. Br J Oral Maxillofac Surg 2009;47:65-6.
11. Feldkamp LA, Davis LC, Kress JW. Practical cone-beam algorithm. J Opt Soc Amer 1984;1:612-9.
12. Gupta R, Grasruck M, Suess C, Bartling SH, Schmidt B, Stierstorfer K, et al. Ultra-high resolution flat-panel volume CT: fundamental principles, design architecture, and system characterization. Eur Radiol 2006;16:1191-205.
13. Hirota S, Nakao N, Yamamoto S, Kobayashi K, Maeda H, Ishikura R, et al. Cone-beam CT with flat-panel-detector digital angiography system: early experience in abdominal interventional procedures. Cardiovasc Intervent Radiol 2006;29:1034-8.
14. Koyama S, Aoyama T, Oda N, Yamauchi-Kawaura C. Radiation dose evaluation in tomosynthesis and C-arm cone-beam CT examinations with an anthropomorphic phantom. Med Phys 2010;37:4298-306.

15. Suzuki S, Yamaguchi I, Kidouchi T, Yamamoto A, Masumoto T, Ozaki Y. Evaluation of effective dose during abdominal three-dimensional imaging for three flat-panel-detector angiography systems. Cardiovasc Intervent Radiol 2011;34:376-82.

16. Braak SJ, Herder GJ, van Heesewijk JP, van Strijen MJ. Pulmonary masses: initial results of cone-beam CT guidance with needle planning software for percutaneous lung biopsy. Cardiovasc Intervent Radiol 2012;35:1414-21.

17. Tam AL, Mohamed A, Pfister M, Chinndurai P, Rohm E, Hall AF, et al. C-arm cone beam computed tomography needle path overlay for fluoroscopic guided vertebroplasty. Spine (Phila Pa 1976) 2010;35:1095-9.

18. Leschka SC, Babic D, El Shikh S, Wossmann C, Schumacher M, Taschner CA. C-arm cone beam computed tomography needle path overlay for image-guided procedures of the spine and pelvis. Neuroradiology 2012;54:215-23.

19. Powell MF, DiNobile D, Reddy AS. C-arm fluoroscopic cone beam CT for guidance of minimally invasive spine interventions. Pain Physician 2010;13:51-9.

20. Busser WM, Hoogeveen YL, Veth RP, Schreuder HW, Balguid A, Renema WK, et al. Percutaneous radiofrequency ablation of osteoid osteomas with use of real-time needle guidance for accurate needle placement: a pilot study. Cardiovasc Intervent Radiol 2011;34:180-3.

21. Morimoto M, Numata K, Kondo M, Nozaki A, Hamaguchi S, Takebayashi S, et al. C-arm cone beam CT for hepatic tumor ablation under real-time 3D imaging. AJR Am J Roentgenol 2010;194:W452-4.

22. Kroeze SG, Huisman M, Verkooijen HM, van Diest PJ, Ruud Bosch JL, van den Bosch MA. Real-time 3D fluoroscopy-guided large core needle biopsy of renal masses: a critical early evaluation according to the IDEAL recommendations. Cardiovasc Intervent Radiol 2012;35:680-5.

23. Möhlenbruch M, Nelles M, Thomas D, Willinek W, Gerstner A, Schild HH, et al. Cone-beam computed tomography-guided percutaneous radiologic gastrostomy. Cardiovasc Intervent Radiol 2010;33:315-20.

24. Hodek-Wuerz R, Martin JB, Wilhelm K, Lovblad KO, Babic D, Rufenacht DA, et al. Percutaneous vertebroplasty: preliminary experiences with rotational acquisitions and 3D reconstructions for therapy control. Cardiovasc Intervent Radiol 2006;29:862-5.

25. Braak SJ, Herder GJ, van Heesewijk JP, van Strijen MJ. Pulmonary masses: initial results of cone-beam CT guidance with needle planning software for percutaneous lung biopsy. Cardiovasc Intervent Radiol 2012;35:1414-21.

26. Heran NS, Song JK, Namba K, Smith W, Niimi Y, Berenstein A. The utility of DynaCT in neuroendovascular procedures. AJNR Am J Neuroradiol 2006;27:330-2.

27. Sato K, Matsumoto Y, Kondo R, Tominaga T. Usefulness of C-arm cone-beam computed tomography in endovascular treatment of traumatic carotid cavernous fistulas: a technical case report. Neurosurgery 2010;67:467-9;discussion 469-70.

28. Aadland TD, Thielen KR, Kaufmann TJ, Morris JM, Lanzino G, Kallmes DF, et al. 3D C-arm conebeam CT angiography as an adjunct in the precise anatomic characterization of spinal dural arteriovenous fistulas. AJNR Am J Neuroradiol 2010;31:476-80.

29. Patel NV, Gounis MJ, Wakhloo AK, Noordhoek N, Blijd J, Babic D, et al. Contrast-enhanced angiographic cone-beam CT of cerebrovascular stents: experimental optimization and clinical application. AJNR Am J Neuroradiol 2011;32:137-44.

30. Miyayama S, Yamashiro M, Okuda M, Yoshie Y, Sugimori N, Igarashi S, et al. Usefulness of cone-beam computed tomography during ultraselective transcatheter arterial chemoembolization for small hepatocellular carcinomas that cannot be demonstrated on angiography. Cardiovasc Intervent Radiol 2009;32:255-64.

31. Louie JD, Kothary N, Kuo WT, Hwang GL, Hofmann LV, Goris ML, et al. Incorporating cone-beam CT into the treatment planning for yttrium-90 radioembolization. J Vasc Interv Radiol 2009;20:606-13.

32. Meyer BC, Frericks BB, Albrecht T, Wolf KJ, Wacker FK. Contrast-enhanced abdominal angiographic CT for intra-abdominal tumor embolization: a new tool for vessel and soft tissue visualization. Cardiovasc Intervent Radiol 2007;30:743-9.

33. Wong KM, Tan BS, Taneja M, Wong SY, Loke JS, Lin SE, et al. Cone beam computed tomography for vascular interventional radiology procedures: early experience. Ann Acad Med Singapore 2011;40:308-14.

34. Deschamps F, Solomon SB, Thornton RH, Rao P, Hakime A, Kuoch V, et al. Computed analysis of three-dimensional cone-beam computed tomography angiography for determination of tumor-feeding vessels during chemoembolization of liver tumor: a pilot study. Cardiovasc Intervent Radiol 2010;33:1235-42.

35. Hirota S, Nakao N, Yamamoto S, Kobayashi K, Maeda H, Ishikura R, et al. Cone-beam CT with flat-panel-detector digital angiography system: early experience in abdominal interventional procedures. Cardiovasc Intervent Radiol 2006;29:1034-8.

36. Jeon UB, Lee JW, Choo KS, Kim CW, Kim S, Lee TH, et al. Iodized oil uptake assessment with cone-beam CT in chemoembolization of small hepatocellular carcinomas. World J Gastroenterol 2009;15:5833-7.

37. Dijkstra ML, Eagleton MJ, Greenberg RK, Mastracci T, Hernandez A. Intraoperative C-arm cone-beam computed tomography in fenestrated/branched aortic endografting. J Vasc Surg 2011;53:583-90.

38. Tam A, Mohamed A, Pfister M, Rohm E, Wallace MJ. C-arm cone beam computed tomographic needle path overlay for fluoroscopic-guided placement of translumbar central venous catheters. Cardiovasc Intervent Radiol 2009;32:820-4.

39. Nesbit GM, Nesbit EG, Hamilton BE. Integrated cone-beam CT and fluoroscopic navigation in treatment of head and neck vascular malformations and tumors. J Neurointerv Surg 2011;3:186-90.